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(54) **SLAB LASER AND AMPLIFIER**

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H01S 3/16 (2006.01)
H01S 3/06 (2006.01)
H01S 3/08 (2006.01)
H01S 3/093 (2006.01)

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(52) **U.S. Cl.**
CPC *H01S 3/0606* (2013.01); *H01S 3/08095* (2013.01); *H01S 3/093* (2013.01); *H01S 3/042* (2013.01); *H01S 3/0407* (2013.01); *H01S 3/0615* (2013.01); *H01S 3/1623* (2013.01); *H01S 3/1625* (2013.01); *H01S 3/1633* (2013.01); *H01S 3/1636* (2013.01); *H01S 3/2333* (2013.01)

(58) **Field of Classification Search**
CPC H01S 3/093; H01S 3/0606; H01S 3/1623; H01S 3/1633; H01S 3/08095
USPC 372/80, 70
See application file for complete search history.

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Primary Examiner — Jessica Stultz

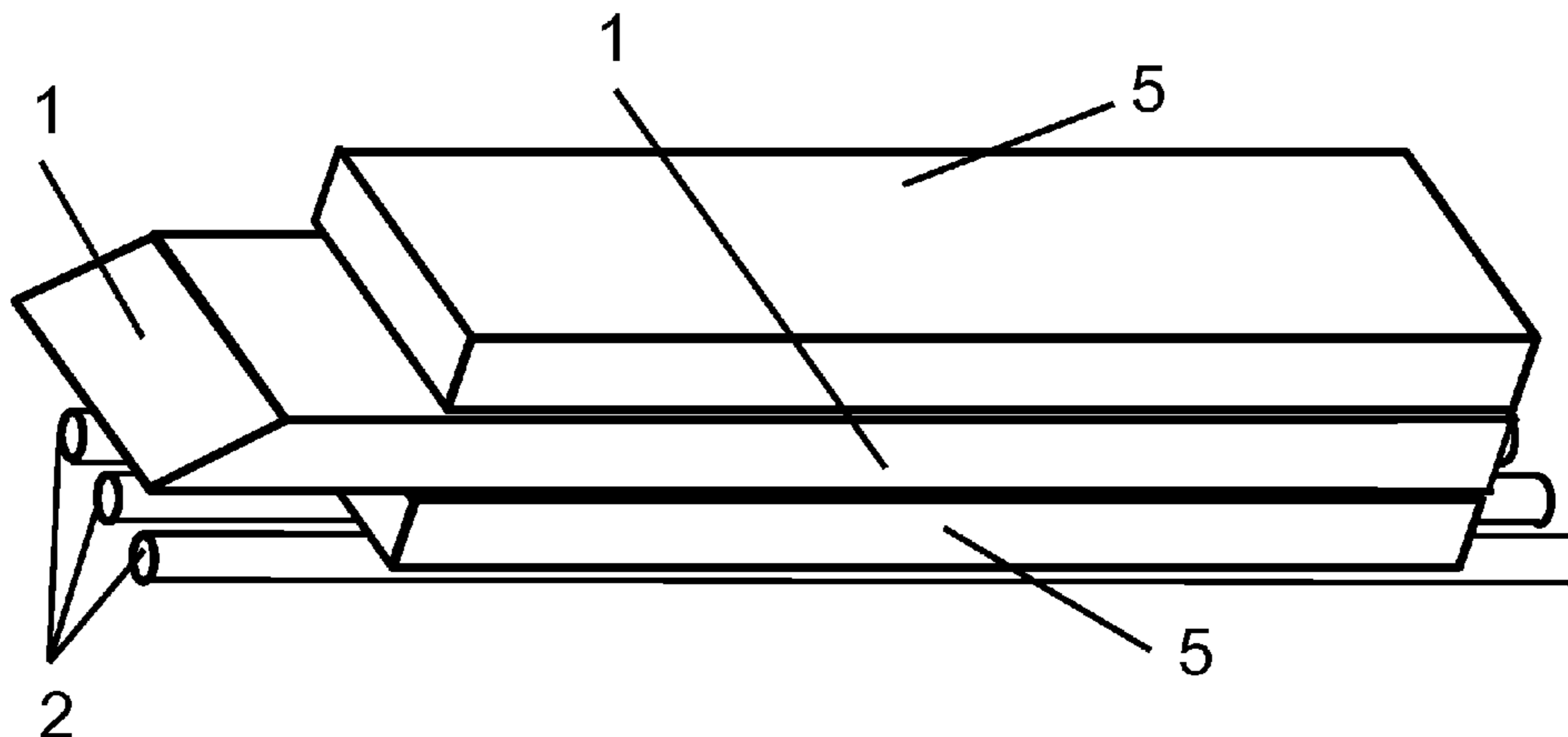
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(57) **ABSTRACT**

An economical slab laser for high power applications. The laser is a lamp driven slab design with face-to-face beam propagation and an end reflection that redirects the amplified radiation back out the input surface. Also presented is a side-to-side larger amplifier configuration, permitting very high average and peak powers due to the electrical efficiency of converting and getting energy into the crystal, optical extraction efficiency, and scalability of device architecture. Cavity filters adjacent to pump lamps convert the unusable UV portion of the pump lamp spectrum into light in the absorption band of the slab laser thereby increasing the overall pump efficiency. The angle of the end reflecting surface is changed to cause the exit beam to be at a different angle than the inlet beam, thereby eliminating the need to separate the beams external to the laser with the subsequent loss of power.

30 Claims, 7 Drawing Sheets



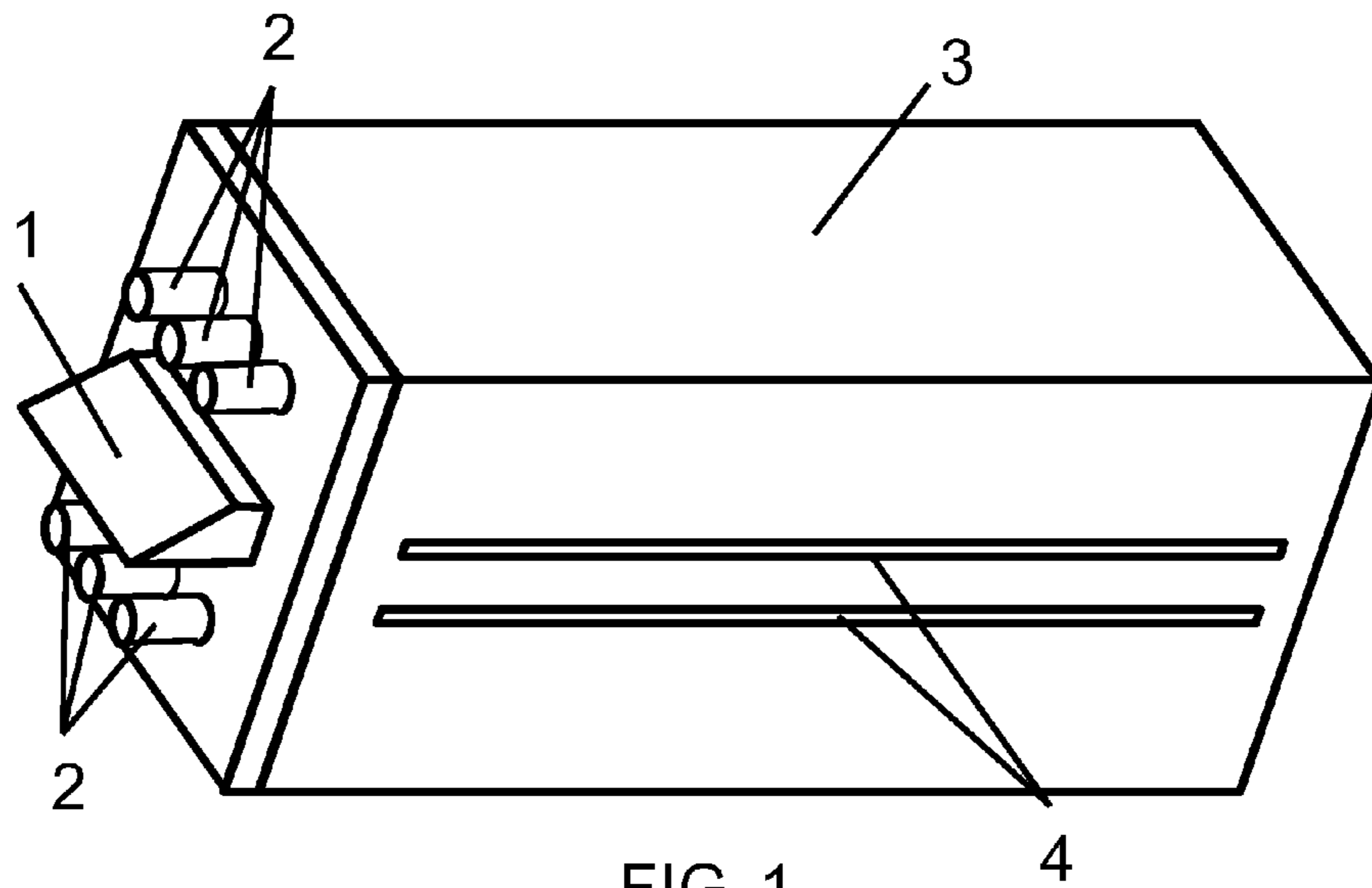


FIG. 1

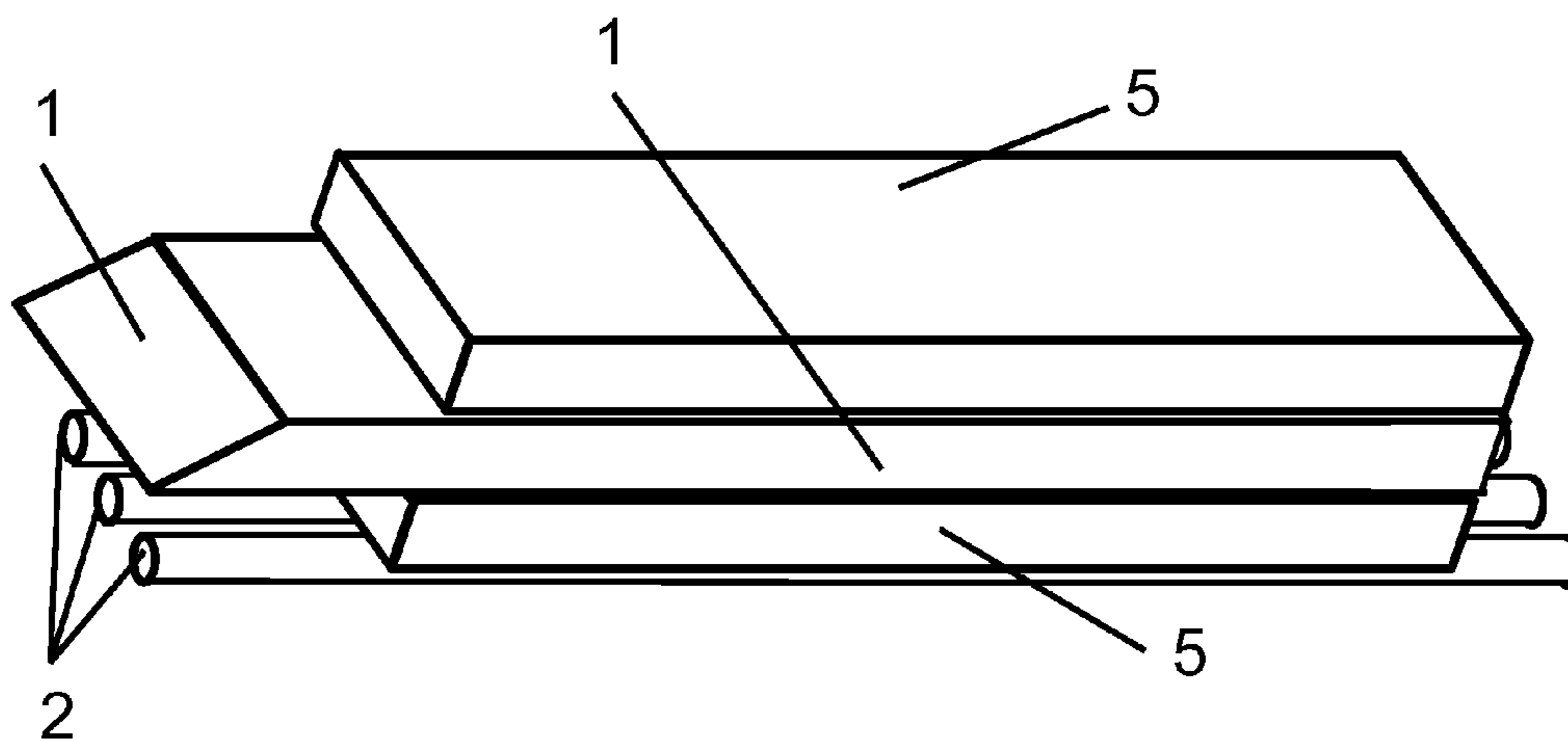
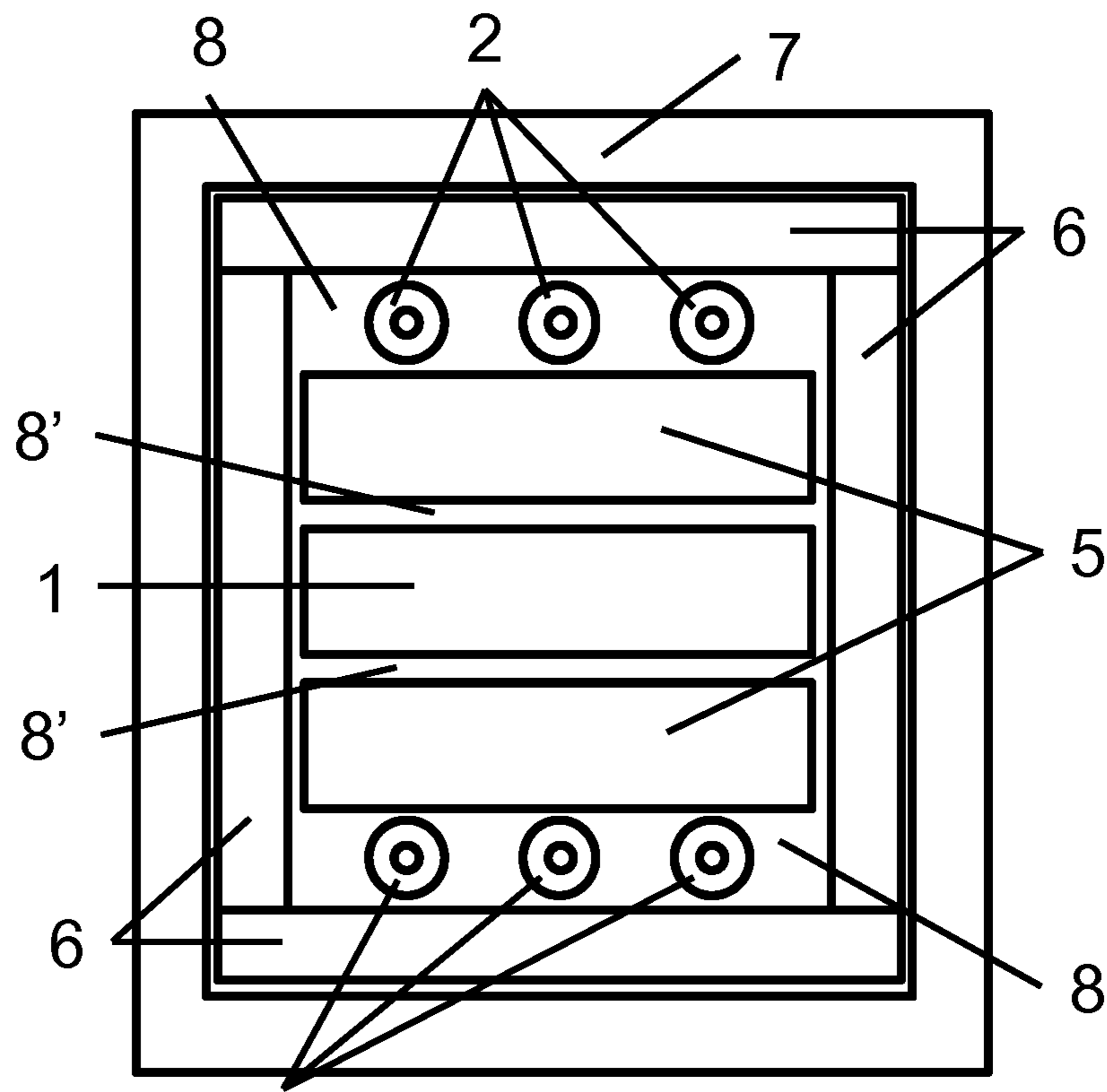


FIG. 2



2 FIG. 3

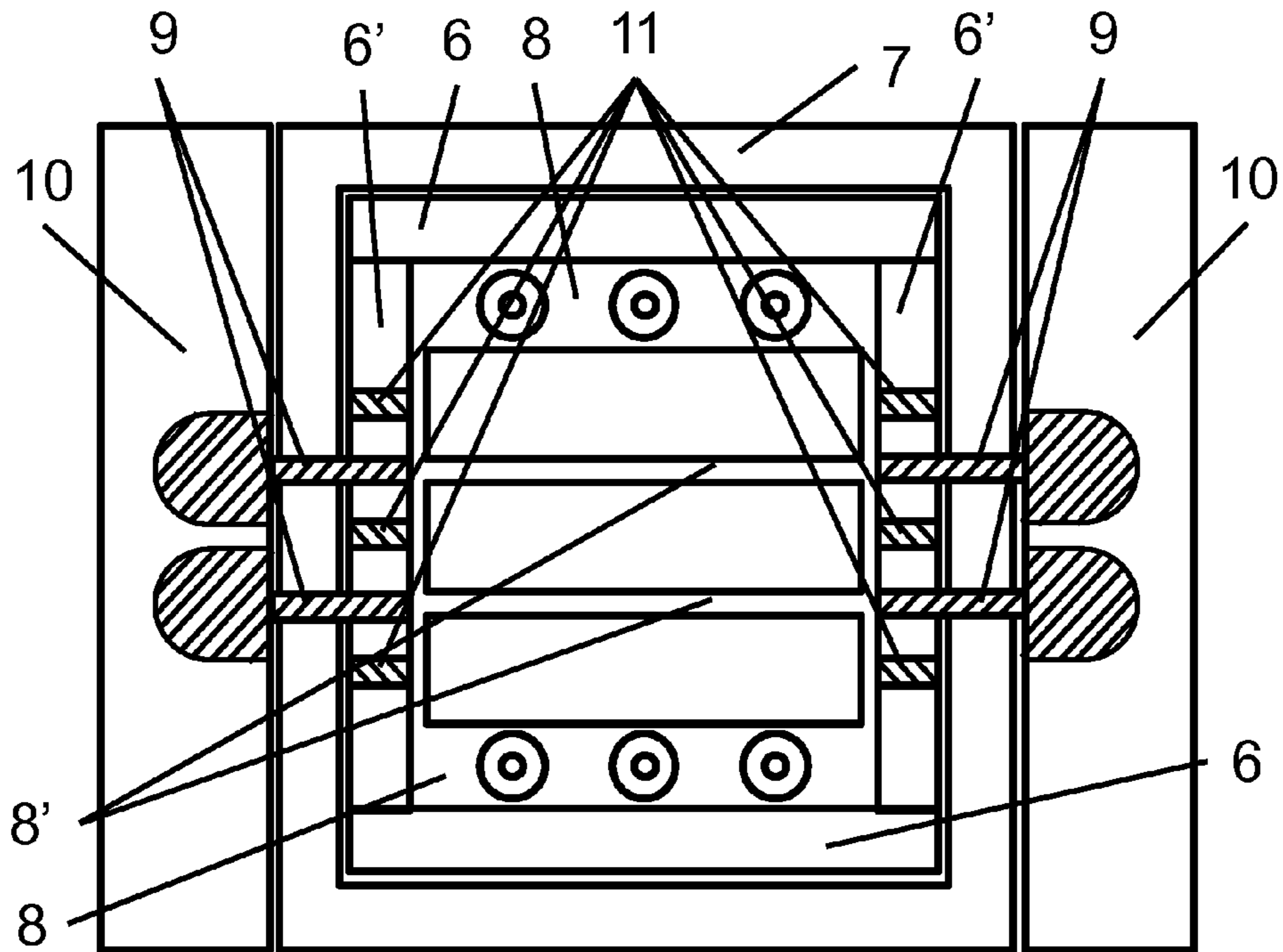


FIG. 4

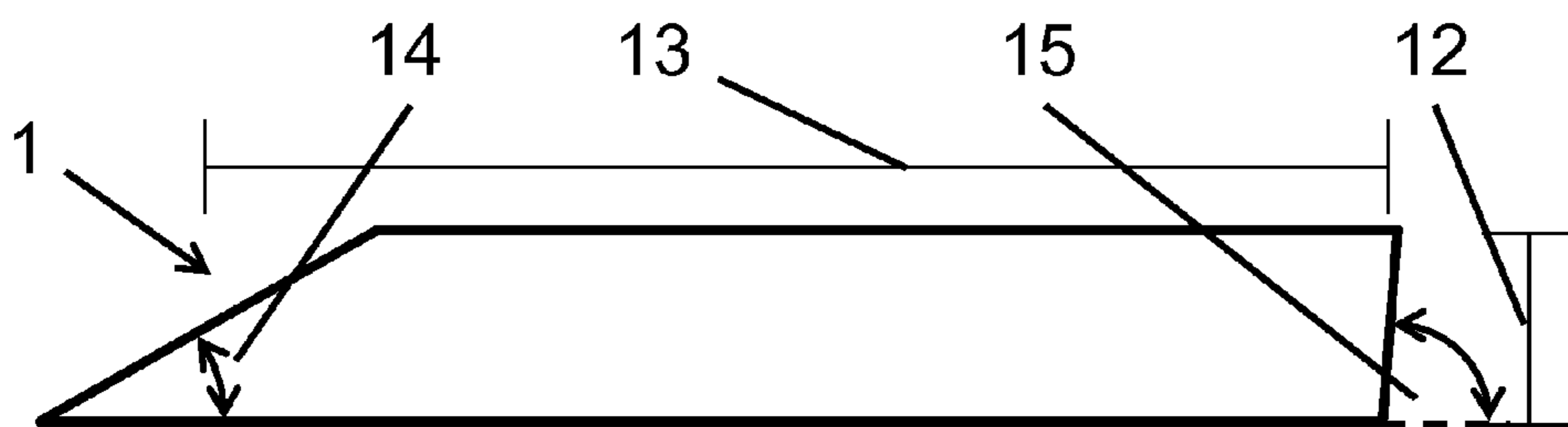


FIG. 5

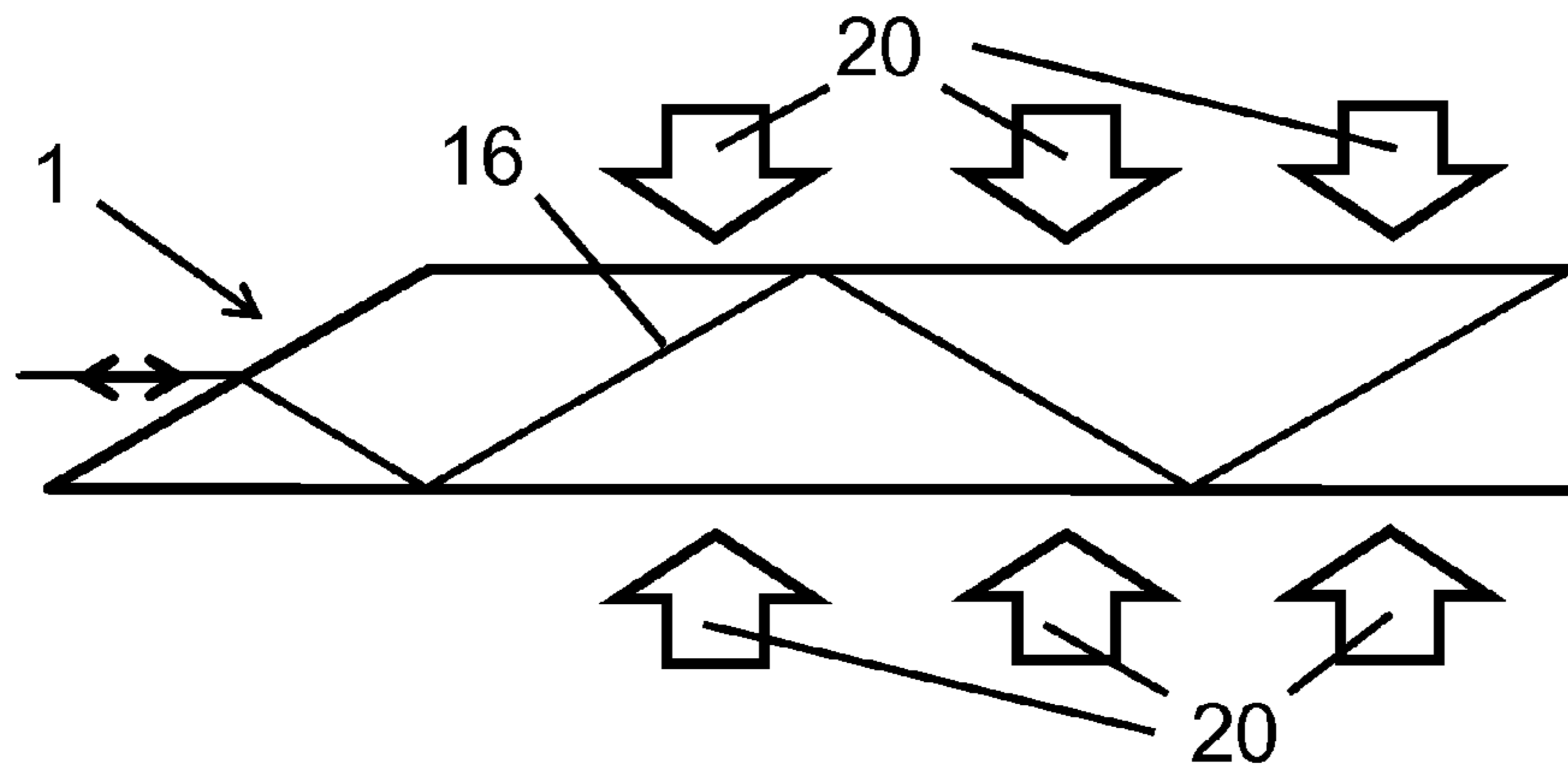


FIG. 6

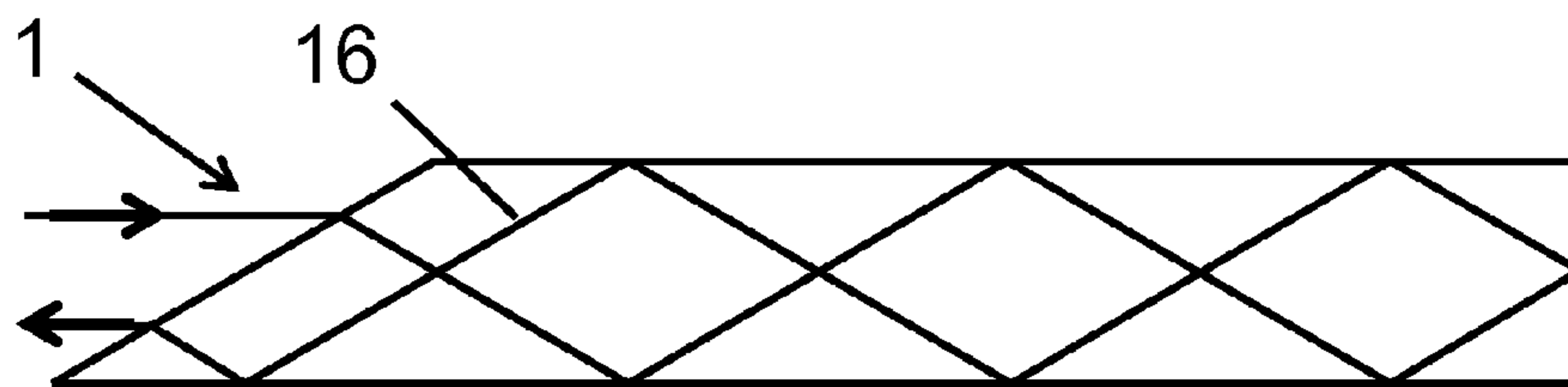


FIG. 7A

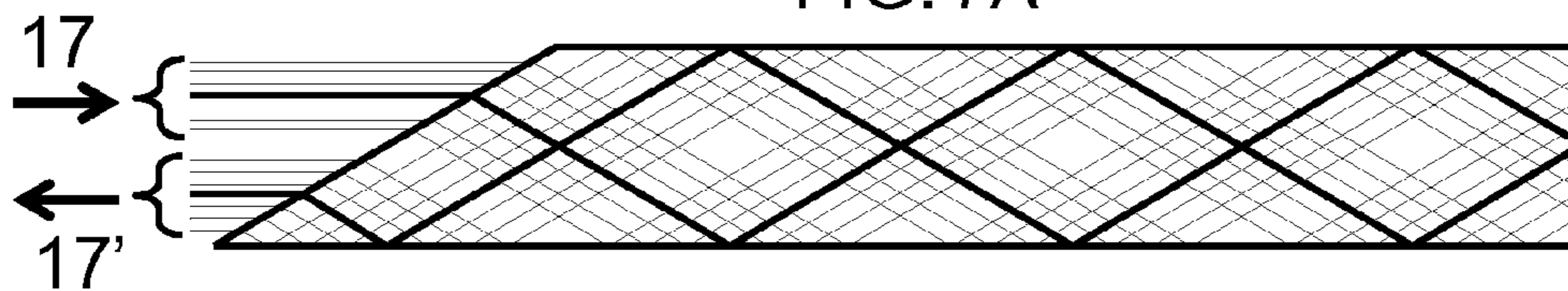
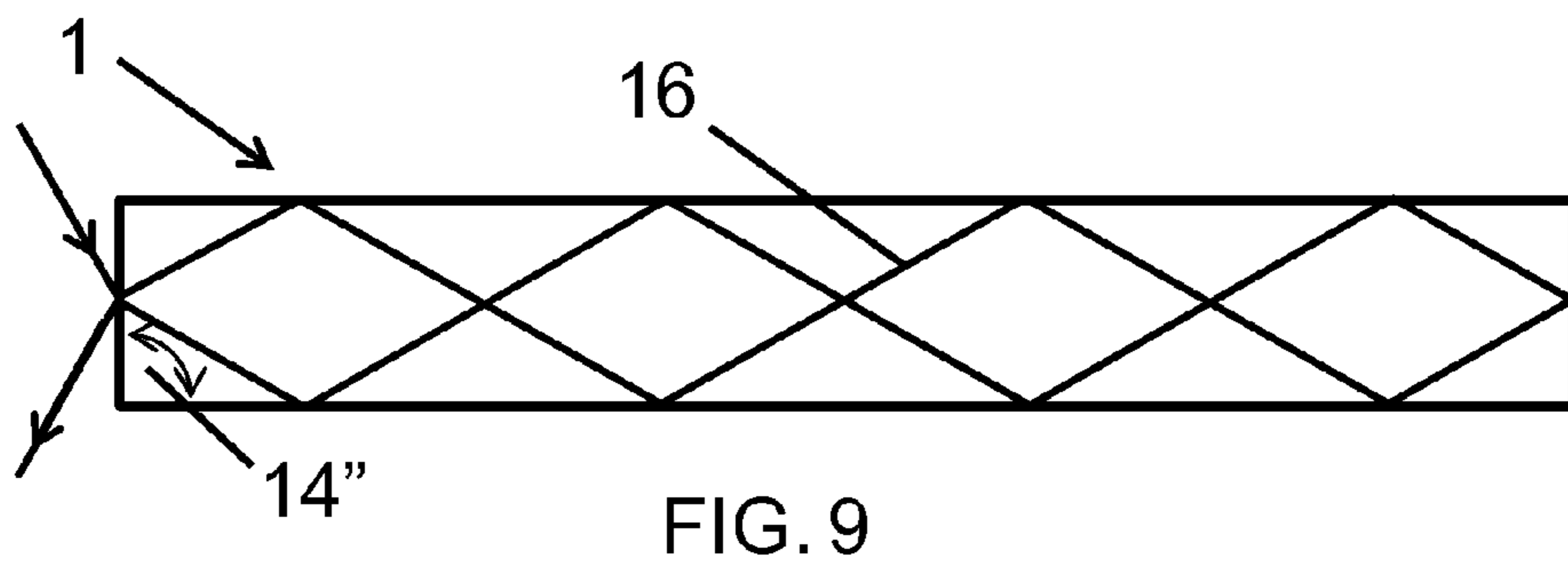
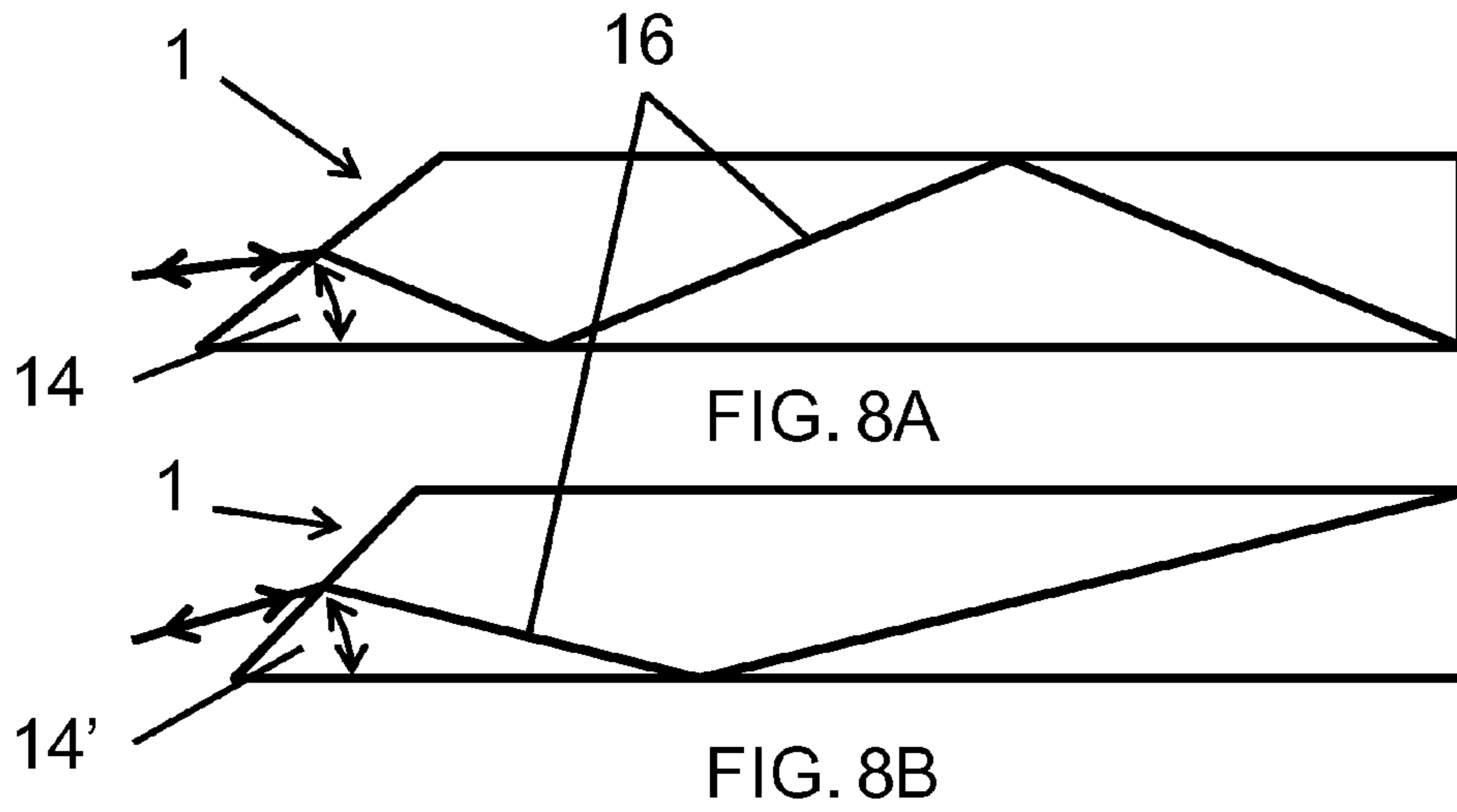


FIG. 7B



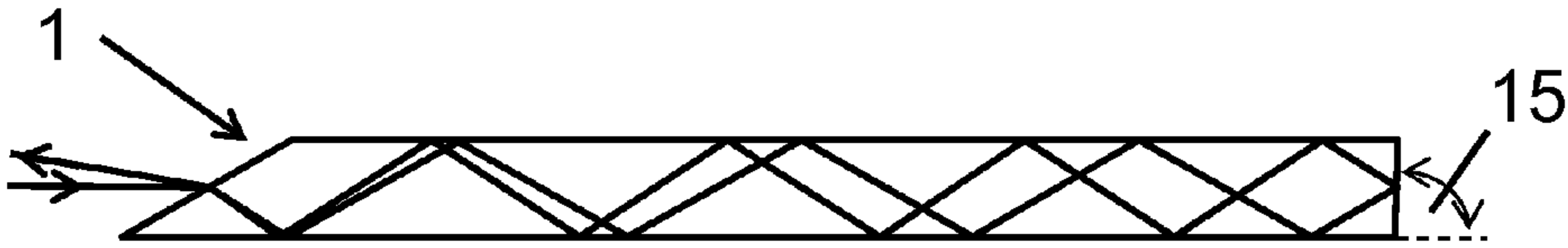


FIG. 10A

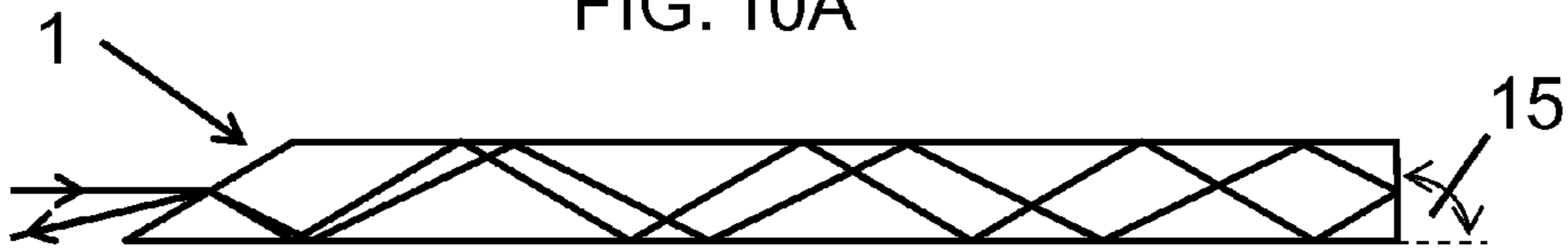


FIG. 10B

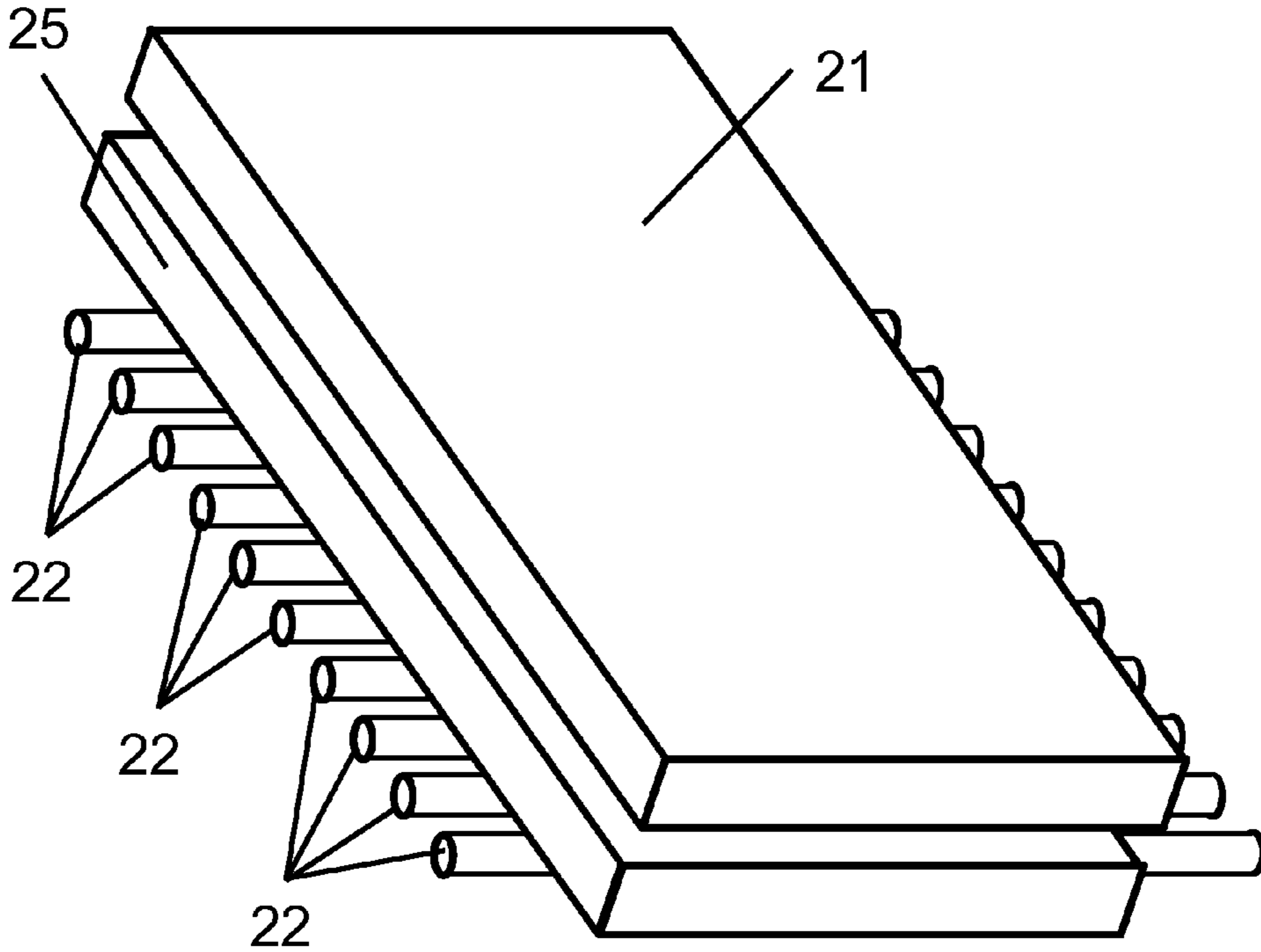


FIG. 11

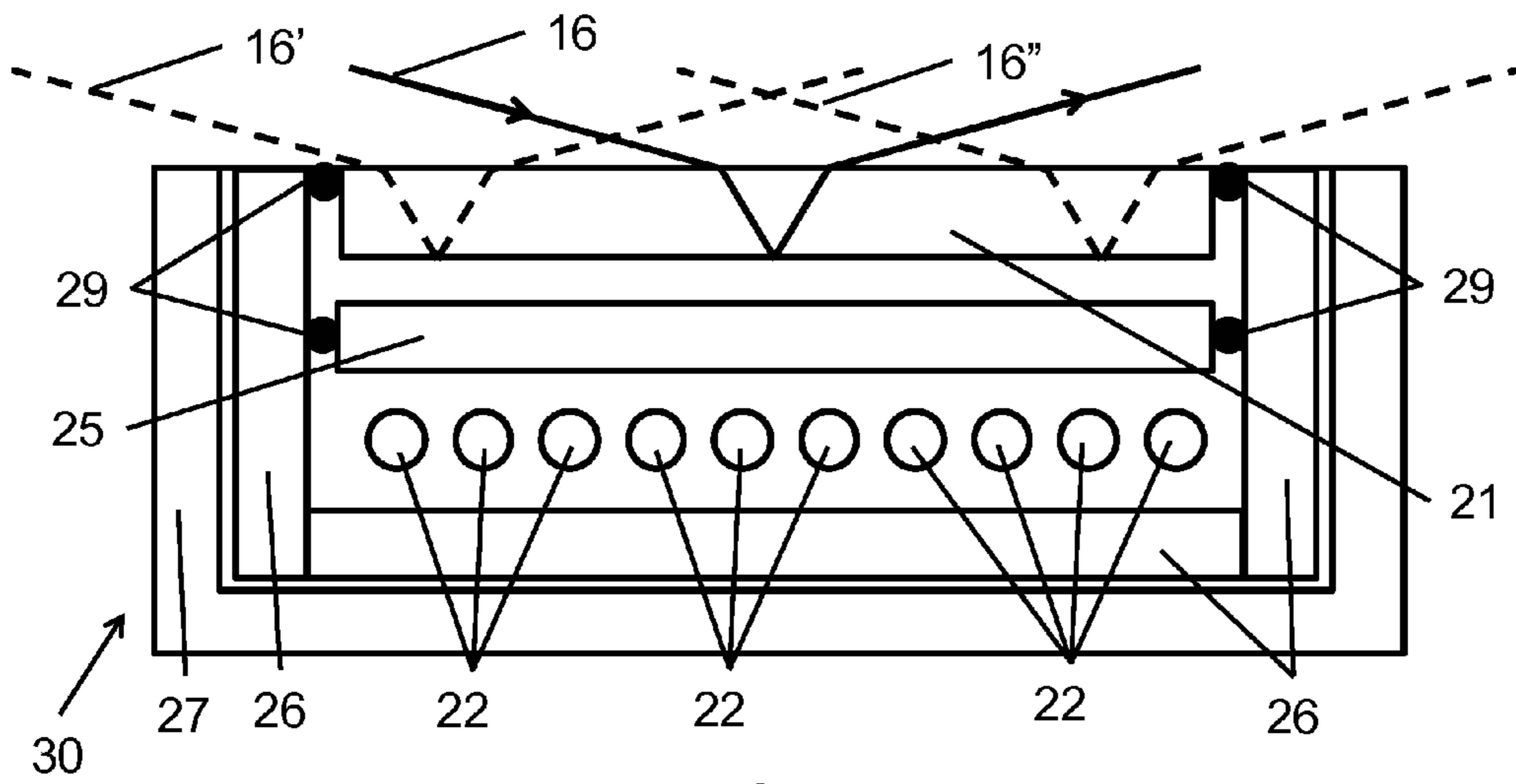


FIG. 12

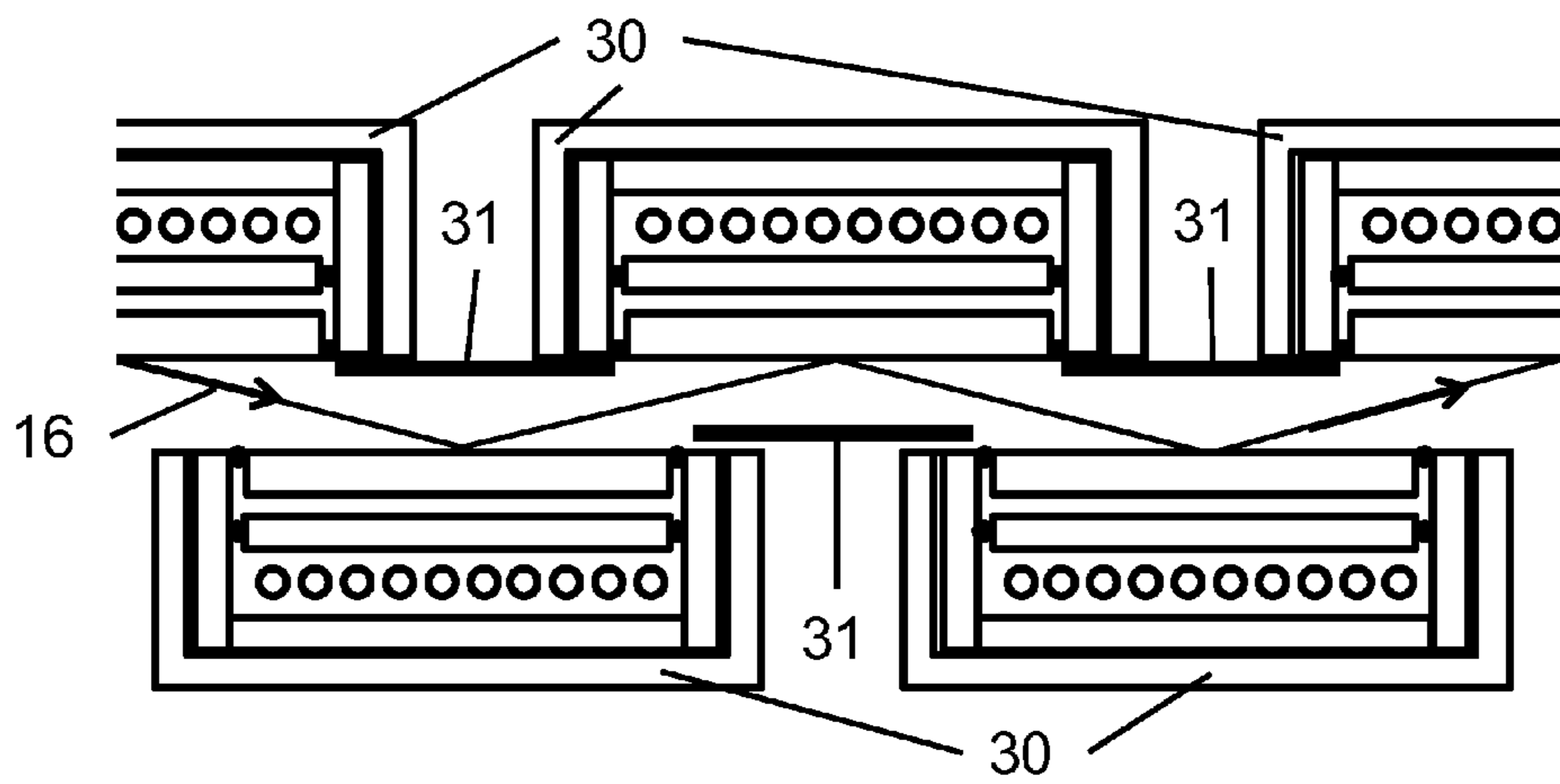


FIG. 13

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SLAB LASER AND AMPLIFIER

CROSS-REFERENCES TO RELATED
APPLICATIONS

This application claims the benefit of U.S. provisional application Ser. No. 61/515,078 that was filed on Aug. 4, 2011, and is incorporated herein by reference.

BACKGROUND

This application relates generally to the field of Lasers and Laser Amplifiers. More specifically, the application relates to solid state laser amplifiers in the form of a slab which are pumped optically by lamps and where the laser beam enters through a Brewster angle facet and experiences multiple face to face bounces due to total internal reflection before exiting through the same face as that the beam entered.

Generally, lamp driven slab lasers have existed for many years. The prior art is exemplified by General Electric's design of a Krypton arc lamp driven, face pumped, face to face multi-bounce, total internal reflection (TIR) Nd:Yag (Neodymium doped Yttrium Aluminum Garnet) slab. In General Electric's design, the Nd:Yag crystal was face pumped with Krypton arc lamps. These particular designs achieved a conversion efficiency (laser power out divided by electrical power in) of ~4% with an output that reached several Kilowatts. In this design, Krypton arc flash or arc lamps (consisting of cerium doped quartz envelopes) discharging a spectrum of blackbody and line emission photons that were subsequently reflected as evenly as possible onto the adjacent faces of the Neodymium doped Yttrium Aluminum Garnet slab. This gain element selectively absorbed portions of this energy. This energy excited the Neodymium atoms into an elevated energy state from which the laser beam was generated or amplified.

Later versions incorporated Diode laser pump sources to increase efficiency and architectural simplicity (by producing only a particular frequency of photonic energy that is highly absorbed by the doped Yag). Still later versions employed Nd doped Ytterbium Vanadate (YbVO₄) as the gain medium. Such systems have become the standard with the limitation being the maximum size that YAG, Vanadate or gain crystals can be fabricated. U.S. Pat. Nos. 3,633,126 and 3,631,362 discuss related technologies.

The previously mentioned diode pumped systems have demonstrated system efficiencies of 10%, with efficiencies that might even approach 25% in ideal circumstances, but at a high financial cost, with the breakdown being approximately 50% efficiency for the diode pump lasers, 65% efficiency for the Nd:VO₄, for Nd:YAG the efficiency has been about 50% conversion to the 1.064 micron radiation, and subsequent beam clean-up reducing the system output efficiency to as low as 10% with the overall efficiency of well-designed systems being about 25%. The current upper limit to the output power has been demonstrated with both Ceramic Yag slabs that were fiber edge pumped and with face pumped versions, both of which were built chiefly by Northrop Grumman. Their system demonstrated an output of 25 kW (Kilowatt) per laser head, with an efficiency of ~50% for the Diode pump lasers, and a conversion efficiency of ~50% in the Nd:Yag slab for an output efficiency at approximately 25%.

The limiting efficiency for the existing lamp pumped designs are primarily in two areas. First is the inefficiency due to the fact that the emitting spectrum from the pump lamps typically does not match the excitation spectrum of the laser crystal material. Second is in the inefficiency of the beam

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extraction from the gain material due to having the beam pass through no more than twice and incompletely fill the gain material. These drawbacks have interfered with potential practical applications of the slab laser concept.

SUMMARY OF THE INVENTION

Presented is a transverse face-pumped, lamp-driven slab laser and amplifier design with a face to face beam propagation scheme. A TIR end bounce redirects the amplified radiation back out the same input facet, but in a different angular direction, making the presented design practical to use in a larger system, if desired.

Also presented is the use of pump lamps that produce more photons in a usable spectrum than previous lamp designs based on noble gases. Cavity fluorescent filters have also been employed that convert a non-useful portion of the lamp output to useful pump bands at a rather high efficiency. This improves efficiencies and power handling capabilities.

Provided as an example embodiment is laser device comprising: a slab crystal, and a cavity filter material provided on at least one side of the slab crystal for receiving light energy from a light source, such that the cavity filter material converts the light energy received at a first frequency band into light energy at a second frequency band that is absorbed by the slab crystal.

For the above laser, the slab crystal is adapted to receive an incident light beam into one end of the slab crystal at one angle and also emits an amplified laser beam from the one end at either an angle different than the one angle or emits the amplified laser beam linearly shifted from the incident light beam after absorbing the light energy at the second frequency.

Further provided is an example embodiment of a laser device comprising: a slab crystal; a light source providing light energy including an ultraviolet frequency band; and a cavity filter material including terbium fluoride doped with samarium that is provided on at least one side of the slab crystal for receiving the light energy from the light source, and for converting the light energy at the first ultraviolet frequency band into light energy at a second frequency band of visible light for absorption by the slab crystal for amplifying a laser beam.

The above slab crystal is adapted to emit the amplified laser beam from an end not including the back reflecting surface.

Also provided is an example embodiment of laser device comprising: a slab crystal; a light source providing light energy including a portion in an ultraviolet frequency band and a portion in a visible light frequency band; and a cavity filter material transparent to the visible light frequency band and that is provided on at least one side of the slab crystal for receiving the light energy from the light source, and for converting the light energy at the first ultraviolet frequency band into light energy at a converted frequency band less than the ultraviolet frequency band for absorption by the slab crystal.

The light source and the cavity filter material of the above laser are arranged such that at least a part of the portion of the light energy in the visible light frequency band is transmitted through the cavity filter to the slab crystal, and the slab crystal is adapted to absorb both a portion of the part of the light energy in the visible frequency band transmitted through the cavity filter and also to absorb a portion of the light energy at the converted frequency band for amplifying a laser beam for emitting from the slab laser.

Further provided is an example embodiment of a laser device comprising: a slab crystal; a light source providing light energy at a first frequency band; a cavity filter material provided on at least one side of the slab crystal for receiving

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a portion of the light energy from the light source, and for converting at least some of the portion of the light energy at the first frequency band into light energy at a second frequency band for at least partial absorption by the slab crystal; a plurality of elastic holders for holding components of the device while allowing for thermal expansion of one or more the components of the device; and a coolant circulation system for circulating a coolant in the device for cooling the device, such that the slab crystal is adapted to emit an amplified laser beam from an end of the slab crystal.

Also provided is an example laser device comprising: a slab crystal having a front face that forms a point provided at an acute angle with respect to a bottom of the slab crystal for receiving an incident light beam provided at a first angle with respect to the front face, the slab crystal also having a back wall that is provided at a back angle that is not 90 degrees with respect to the bottom of the slab crystal; a light source providing light energy including a portion in first frequency band and a portion in a second frequency band; and a cavity filter material transparent to the first light frequency band and that is provided on the top or the bottom of the slab crystal for receiving the light energy from the light source, and for converting the light energy at the first frequency band into light energy at a converted frequency band for at least partial absorption by the slab crystal.

The light source and the cavity filter material of the above laser are arranged such that at least part of the portion of the light energy in the second light frequency band is transmitted through the cavity filter to the slab crystal, and furthermore the slab crystal is adapted for amplifying a laser beam for emitting from the slab crystal by absorbing both a portion of the part of the light energy in the second frequency band transmitted through the cavity filter, and is by absorbing a portion of the light energy at the converted frequency band.

For the above laser, the acute angle and the back angle are chosen such that the amplified laser beam is emitted from the front face of the slab crystal at an angle that is different than the first angle such that the incident light beam entering the slab crystal is not coincident with the amplified laser beam emitted from the slab crystal.

Further provided is a laser amplification system using any plurality of any of the above lasers in series for amplifying a light beam.

Also provided are additional example embodiments, some, but not all of which, are described hereinbelow in more detail.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the example embodiments described herein will become apparent to those skilled in the art to which this disclosure relates upon reading the following description, with reference to the accompanying drawings, in which:

FIG. 1 is a schematic drawing of an external view of one example embodiment of the invention;

FIG. 2 is a schematic drawing showing two layers of a filter cavity material that are provided on both sides of slab laser material;

FIG. 3 is a schematic drawing of an end view of the example embodiment of the invention of FIG. 1 showing a relation between the laser slab, two cavity filters, pump lamps, a ceramic reflector, and an external case;

FIG. 4 is a schematic drawing of another example embodiment adding an external water manifold for cooling;

FIG. 5 is a schematic drawing of a general cross-section geometry of a laser slab of the example embodiment;

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FIG. 6 is a schematic drawing of a path of the on-axis laser beam entering and leaving the amplifier slab of an example embodiment;

FIG. 7A is a schematic drawing of an effect of displacing a laser beam to get separation of an exit beam from the entrance beam for the example embodiment;

FIG. 7B is a schematic drawing of an effect of displacing a plurality of laser beams for the example embodiment shown in FIG. 7A;

FIGS. 8A and 8B are schematic drawings showing an effect of varying an angle of a wedge at the front of the laser slab in the example embodiment;

FIG. 9 is a schematic drawing of an example arrangement for providing an entrance and an exit beam in different directions beam for the example embodiment;

FIGS. 10A and 10B are schematic drawings showing example separation of the exit beam from the entrance beam by varying the angle of an end reflecting surface in the example embodiment;

FIG. 11 is a schematic drawing showing an interior structure of one section of an example amplifier chain using a large slab laser crystal and adding more pump lamps;

FIG. 12 is a schematic drawing showing a cross section of one of the amplifiers in a chain showing how the laser beam enters and exits the gain material; and

FIG. 13 is a schematic drawing showing an example of combining a plurality of the amplifiers of FIG. 12 in series to provide very high laser output powers.

DETAILED DESCRIPTION OF THE INVENTION

As discussed above, provided is an example embodiment of a transverse face-pumped, lamp-driven slab laser and amplifier design with a face to face beam propagation scheme. A TIR end bounce redirects the amplified radiation back out the same input facet, but in a different angular direction, making the presented design practical to use in a larger system, if desired. By this choice of geometry, the pulse of laser light to be generated or amplified, passes through the same piece of gain material at least four times (not the normal two times) in each round trip inside the laser slab. Under the conditions of energy extraction efficiency being ~60% per pass, this would result in about 97% of the stored energy in the laser slab being extracted. This feature contributes to the higher efficiency of the example device.

Also presented a further example embodiment is the use of pump lamps that use metal or metal halides which produce more photons in a usable spectrum than previous lamp designs based on noble gases. Cavity fluorescent filters have also been employed that convert the non-useful portion of the lamp output (in the ultraviolet portion of the spectrum for the Mercury arc lamps and Indium Iodide plus Thallium Iodide lamps for the Ti Sapphire laser) to useful pump bands at a rather high efficiency. These improvements result in a system that operates with efficiencies and power handling capabilities normally associated only with diode laser pumped versions. But the example system presented here achieves these efficiencies using lamps instead of laser diodes, and can therefore be very much less expensive to implement for the same amount of output power than prior designs using diode laser pumps.

For the presented gain materials utilized in the example designs, the presented lamp pumped designs will have power output levels that exceed the diode pumped versions of these lasers for the same size. For example, the efficiency of the visible light output (635-670 nm and 680.4 nm red light) from pump lasers utilized for Alexandrite devices operate at

approximately 20% efficiency conversion. Also, the frequency doubled Nd lasers, which output 532 nm green light, used to pump Titanium Sapphire's green absorption band, also operate at about 20% electrical to optical conversion efficiency. By comparison, the electrical to optical efficiency of metal arc and metal halide arc lamps are both near 70-73%. This improvement and architecture can be used to amplify pulsed or continuous wave laser beams to very high power levels with a system efficiency that has an upper limit of over forty percent. The per head output is expected to be in the 6.5-15.5 KW range for the head design presented, but the designs are not limited to these power levels.

Overall Laser Device Configuration

FIG. 1 shows a schematic of the general configuration of one example embodiment of this invention. The ends of the slab crystal 1 and of the six pump lamps 2 extend outside of the housing 3. The housing allows for liquid cooling through slots 4. These slots 4 enter a water manifold external to the housing 3 as will be discussed later.

FIG. 2 shows where cavity filter slabs 5 reside inside the housing on both sides of the laser slab crystal 1. In this figure, only three of the six pump lamps 2 are shown for clarity. The purpose of the cavity filter slabs 5 is to convert the ultra-violet portion of the light emitted from the pump lamps 2 into the visible spectrum where it is more readily absorbed by the slab laser crystal 1 material.

FIG. 3 shows a schematic of an end view of the example embodiment showing the primary elements inside the general casing. The center of the structure is the laser slab crystal 1 surrounded on top and bottom by the cavity filter slabs 5 with gaps 8'. The six lamps 2 used to pump the laser crystal 1 are provided outside the cavity filter slabs 5. Surrounding these components are four ceramic reflectors 6 which are encased in a housing 7, which can be made of stainless steel. The housing 7 in FIG. 3 can be the same type as the housing 3 in FIG. 1, but that is not a requirement. In the gaps 8' and 8 between the structures there is provided a coolant, such as cooling water, which flows to cool the lamps 2 and the slab crystal 1.

FIG. 4 shows an example embodiment providing water manifolds 10 used to cool the laser. Two manifolds 10 cover slots 9 that extend through the external case 7 and through the ceramic reflectors 6'. Water is made to flow in opposite directions through the two slots 9 and through the gaps 8' to cool the central laser slab 1. Water also flows in a separate circuit in the axial direction (in the direction of the pump lamps 2 in FIGS. 2 and 3) in gaps 8 to cool the pump lamps 2. The temperatures of the cooling water for the slab laser crystal 1 and for the pump lamps 2 can be different, since they are on separate circuits (described below) which allow for the slab to operate at an efficient temperature that is higher than that of the lamps.

In addition, in the example of FIG. 4 there are holes 11 drilled in the ceramic reflectors 6' which are placed every few inches along the length of the laser slab 1 and the cavity filter slabs 5. These holes allow for silicon or Teflon bumpers to be used to support the respective slabs and to absorb differences in thermal expansion as the laser elements heat up and thus expand. In addition, the silicon forms a water seal to keep the water between the slab laser crystal 1 and the cavity filter slabs 5 separate from the different temperature water that is cooling the pump lamps 2.

The Slab Laser Crystal

In one example design, the slab laser crystal 1 is comprised of Chromium doped Alexandrite ($\text{Cr:BeAl}_2\text{O}_4$), but in another example the slab laser crystal can be comprised of Titanium doped Sapphire. The bulk of the slab crystal is made

up of the doped material. But it could also subsequently be processed with un-doped sections of Alexandrite crystal (BeAl_2O_4) or for the Ti Sapphire, clear undoped Sapphire on the edges and ends via diffusion bonding to produce clear caps. The purpose of the clear cap sections is to reduce the lens distortion due to thermal gradients produced at high pumping powers. These clear caps reduce the distortion effect by a factor of three as the undoped portion has no heat load from left over or un-extracted energy from the gain material.

The preferred crystal growth method to produce the laser slab crystal would be via the classic Heat Exchange Method (HEM). This crystal growth technology produces inclusion-free crystals for either of the example gain materials. By this method, damage free power limits of up to 23 gigawatts per square centimeter can be realized for the Alexandrite material (with similar power handling capability results for the Sapphire material as well). On the other hand, in amplifier configurations where the Czochralski crystal growth method is used, Alexandrite crystals can be produced with a power limit of 1-1.5 gigawatts per square centimeter radiance for 1 nanosecond pulse lengths. These damage values are well above the planned typical operating powers, which could be hundreds of mega-Watts per square centimeter.

Subsequent to obtaining the slab crystal for the laser slab, a reflective coating, such as of silicon dioxide measuring about a micron thick, can be applied to the sides and possibly the edges to act as a reflector for the amplified laser light and to protect the seals where they may overlap a bounce site.

If the designer so desires, the diffusion bonded clear caps can be omitted from the sides and the slab crystal can be enclosed on the sides inside the alumina ceramic cavity reflector with the added design element that a dielectric mirror coating be applied to the two sides and the end of the crystal to facilitate the desired reflections of the amplifying beam. This variation would permit a single seal, compressed around the body of the crystal.

The Pump Lamps

Example pump lamps 2 can utilize Mercury filled (e.g. with a 7 Torr Argon co-fill) clear polished sapphire envelopes or clear fused silica envelopes. Particularly when Sapphire is utilized, Kovar, which is a high nickel alloy that can be used in such lamps as it has a nearly matching expansion coefficient and can be brazed to the envelope using industrially standard techniques. Tungsten electrodes are brazed to the Kovar and are the electrodes establishing the arc in the Mercury.

The lamps built and energized in such a manner have an efficiency of about 72% for Mercury and about 70% for Thallium Iodide. These example lamps are best driven with a high frequency AC power supply. Such power supplies are commercially available and are referred to as ballasts, with operating frequencies of 40-100 kHz. The lamp is sized by choosing the waste heat removal rate (e.g., 240 W/cm² surface area using de-ionized water), and scaling to a useful size. A lamp with a bore diameter of 4.5 mm running at 135 V/cm will pass about 5.8 amps. For a Mercury arc lamp, once the plasma has been established in the bore and the mercury has been vaporized, the impedance characteristics are such that even if the applied voltage is tripled the current will only increase by twenty percent or so. Thus, lamps 1 foot long can be run as high as 35 KW or about 1000 watts per cm. However, for long life, the power is reduced to ~400 watts per cm and the length is shortened. Normal practice is to use a 6 mm diameter fused clear quartz with a 2 mm bore about 15 cm long. In these lamps energized with an AC power source, there is about a 10% per electrode heat loss and care must be paid to this as unsupportable heat loads can be generated.

The Cavity Filter Slabs

Example cavity filter slabs **5** as shown in FIGS. **1-3** are each made up of a rectangular block crystal comprised of Terbium Fluoride (TbF_3) doped with ~0.1% Samarium, which has absorption bands that encompass most of the ultra-violet spectrum. The transfer of energy to the Samarium ion is a nearly lossless non-radiation transfer via the crystal matrix. The crystal then fluoresces at near the absorption band of the Alexandrite crystal, converting otherwise wasted UV energy to useful visible light and thereby increases the pump efficiency of the system. There is a residual heat load from the energy difference between the average input frequency and the specific emission frequency. This is called the Stokes shift. The difference is responsible for residual heat in the crystal even if all or most of the available energy is extracted.

The spectral output of Mercury lamps at this power level is approximately $\frac{1}{3}$ in the UV. Thus, the use of the cavity filter slabs to recycle as much of the UV radiation energy as possible is desirable for increased efficiency. In addition, the Terbium Fluoride filter slabs reduce the amount of UV radiation that impinges on the Alexandrite crystal. That radiation, over time, would likely damage the crystal and reduce its transparency which, in turn, limits its usefulness and thus the useful life of the laser device.

Other crystal designs are feasible to use for the cavity filter slabs as well. These include (but are not limited to) Terbium Garnet with Titanium doped Sapphire gain material; Terbium, Cerium, Titanium doped YALO; Gadolinium, Gallium, Terbium, Cerium, Samarium doped YAG; Terbium Fluoride doped with Samarium; and Terbium-Samarium doped Yttrium Lithium Fluoride. Each has its own specific advantages. Most are less efficient than Terbium Fluoride doped with Samarium, but the oxide crystals can handle higher power input levels with the offset that greater heat would be left behind due to lower conversion efficiency.

Cavity Reflectors

The example ceramic cavity reflector **6, 6'** as shown in FIG. **4** can be comprised of a non-degrading ceramic including a high purity Al_2O_3 (Alumina) composition. It component can be finished with a sealing glaze that allows for a water tight seal on its edges via compressed silicon rubber seal, preferably white or clear.

The arrangement of the ceramic reflectors **6, 6'** resembles a rectangular tube with two rectangular slots at each end to facilitate water flow in the open space **8** along the length of the lamps **2**. This also cools one face of the cavity filter **5**. Additionally, there are square reflector end caps at each end of the pump chamber, in which there are holes allowing the lamps to pass through. There is a separate seal compression plate to allow O-ring seals, of silicon rubber, to be compressed against the lamp walls and the reflector end. At one end there is a rectangular hole for the laser slab to fit through and be sealed via compression O-ring and seal plate.

At the top and bottom outside, near the ends, there are provided two additional attachments allowing water to enter and exit each side (not shown). This is for receiving the cooling water for the lamps and partially for the cavity filter.

Shape of Slab Laser Crystal

FIG. **5** shows the side view of the general shape of the example slab laser crystal **1**. The shape is defined by a slab width **12**, a slab length **13** as measured from the midpoint of each end, a wedge angle acting as a Brewster optical window **14** for the face where the incident and exit beams pass through, and an angle **15** for the reflecting end of the crystal. All four of these parameters are interconnected in the example embodiments, and the slab laser crystal **1** should have a specific set of these parameters for desired functioning.

FIG. **6** shows a preferred example situation where the reflecting angle **15** is provided at 90 degrees and the entrance angle is set by the Brewster angle (for example, the Brewster angle for Alexandrite C axis is 60.06 degrees so the wedge angle **14** of the entrance surface is 29.94 degrees), then the desired slab length is uniquely related to the slab width. For the case of the entrance laser beam **16** located on the center line, the length should be such that the beam center impinges on the corner of the slab at the reflecting end so that the exit beam is also on the center line. For the case shown in FIG. **6**, the incident and exit beam **16** are always co-linear. The light **20** from the pump lamps enters the top and bottom faces of the slab while the source laser light enters, and the amplified laser light exits, via the Brewster angle surface.

When the incident beam is displaced up or down relative to the front surface of the slab, then the exit beam is also displaced in the opposite direction. This is shown in FIG. **7A**, where the single incident beam **16** is halfway between the centerline and the edge of the entrance window. Then, if the incident beam (or plurality of beams) is only half of the size of the window as shown by **17** in FIG. **7B**, then the exit beam **17'** is physically separate from the incident beam **17**. This configuration solves the problem of the separation of the beams, but limits the beam cross sectional area to be less than half of the size of the slab face.

The front wedge angle **14** is not necessarily required to be set to the complement of the Brewster Angle as in the previous figures. As the angle of the wedge changes, the internal reflection angles of the beam **16** inside the slab changes, and the number of reflections for a given total length changes. Two examples of other incident wedge angles that work for the same length and width are shown in FIGS. **8A** and **8B**. In the first example of FIG. **8A**, the wedge angle **14** is 37.6 degrees, and in the second example of FIG. **8B** the wedge angle **14'** is 46.2 degrees. It is always possible to find a slab length that will work for a wide range of angles. In all such cases, however, the incident and exit beams are on top of each other (coincident) in the opposite directions.

However, there is a range of angles near 90 degrees which can also be used. One such condition is shown in FIG. **9**, where the front surface angle **14''** is at 90 degrees relative to the slab axis. For the solutions around this angle, the exit beam and the entrance beam are not aligned. This has the good feature of separating the input and output beam **16**. However, the area of the front surface is at a minimum compared to other wedge angles **14** and **14'**, and this limits the power density of the amplified light.

Finally, preferred example embodiments provide for the reflecting surface at the end of the slab to be at an angle different than 90 degrees. This is shown in FIGS. **10A, 10B** for two example angles **15** and **15'**. In the first example of FIG. **10A**, the end angle **15** is at 88.25 degrees, and this results in the exit beam being separated by 9.41 degrees from the on axis input beam. In the second example of FIG. **10B**, the angle **15'** is 91.80 degrees, and the exit beam is separated by 13.50 degrees from the input beam. Other angles can be used depending upon the ratio of slab length to slab width, and these two are only shown as examples. This configuration has the desirable features of separating the input and exit beams and allowing for the full aperture to be filled with the incident beam.

Another example design using the same materials and general arrangement discussed above but with a slightly different architecture is partially shown in FIG. **11**. This variation would permit scaling to much higher power levels. In this example, there is one row of lamps **22** provided on only one side of the gain crystal **21**, and there are more of them. Instead

of three lamps on the one side for the presented four cm wide crystal example in FIGS. 1-4, there could be up to 24 lamps for a 30 cm long crystal, for example. Also the crystal axis is laterally rotated such that the B axis is along the 30 cm dimension. Also shown is a single cavity filter slab 25 that lies

between the pump lamps 22 and the laser gain material 21. FIG. 12 shows a cross section of the example of one of the segments 30 of an example laser amplifier chain, where the segment 30 incorporates the structure in FIG. 11. This figure shows the laser amplifier slab 21, the cavity filter slab 25, and the array of pump lamps 22. Also shown is the ceramic cavity reflector 26 which covers only one side of the amplifier slab 21, and a stainless steel case 27. The gaps between the amplifier slab 21 and the cavity filter 25 allows for the passage of cooling water as before, and the space around the pump lamps 22 also allows for a separate circuit of cooling water. The slabs are held in place by seals 29 that keep the water circuits separate and allow for the thermal expansion of the parts as the temperature increases.

Also shown in FIG. 12 is the path of the amplified laser beam. The center of the beam is shown by a solid line 16 as it impinges on the surface of the gain crystal 21 at the Brewster Angle. The beam refracts (changes angle) as it crosses the surface, is totally reflected off the back surface, and exits at the Brewster Angle. The beam is wide, as indicated by the dashed lines 16' and 16" and traverses through the gain medium twice (in and out).

FIG. 13 shows how the amplifier stages 30 could be combined into an amplifier chain to result in an amplified beam of extremely high power. The laser beam 16 alternately passes through each one of the amplifier stages 30 on each side of the beam path. Between each amplifier stage, there is a reflecting surface 31 which traps the pump lamp photons in a cavity until they are absorbed by the laser gain material.

At the lower power levels, the laser amplifier could be constructed using the example lasers discussed with respect to FIGS. 1-4. As the power level increases along the amplifier chain, the amplifiers could change in design to the example configuration shown in FIGS. 11-13. The result is a very high power beam at higher efficiencies than previously possible, up to power handling limit of the exemplified gain materials grown via the HEM method. The laser beam is expanded in cross section so this architecture presents a large surface area slab for the beam to interact with. The size of the head is limited only by the size of the HEM furnace producing the boule, from which the slab crystal is cut. For example, if this configuration is made in a 15 cm high by 30 cm long active slab that is 1 cm thick, utilizing a beam cross section of ~15 cm x 15 cm, it would generate a beam with an enormous amount of peak and average power in a simple and relatively small device.

However, even if a larger slab amplifier crystal is assembled via the described methods such as diffusion bonding, the optimum pump lamp size is limited to ~15 cm in length or 6 Kilowatts of power for 6 mm diameter 2 mm bore envelopes. This limit is due to the 20% heat deposited in the electrodes (corresponding to 10% each end if operated on an AC waveform input). The electrode acting as an Anode gets the heat deposition, which occurs on each half cycle. This heat load is manageable in 6 mm diameter quartz tube with a long life. Different dimensions will have different heat removal characteristics and hence different lifetimes. If this pump lamp power and length is chosen to be used with larger slab crystals, then the lamp would be constructed with the electrode sections entering at 90 degree arms with the 15 cm arc section between them in an abbreviated "U" configuration. This type of lamp would be mounted in staggered par-

allel sockets through the back reflector such that rows shown in FIG. 11 would be replaced with arrays. The arrangement could be such as to achieve uniform pump light intensity with either Thallium Iodide or Mercury arc lamps used with either Alexandrite (Mercury lamp) or Titanium Sapphire (Thallium Iodide lamp) laser slabs.

Alternate Materials

A variation of the above described designs is to use Thallium Iodide along with Mercury as the fill in the arc lamp (this changes the spectrum of the pump light, reference U.S. Pat. No. 7,061,182 that is incorporated by reference, which if modified to include cooling capability and have higher power loading, could be used as the pump light source to provide a longer lifetime at the cost of lower efficiencies). Another option is to use Indium Iodide as the fill inside the sapphire lamps with the Titanium doped sapphire (Ti: Al₂O₃) as the laser slab gain medium. In the case where Indium Iodide lamp is used, a cavity filter would also be desirable for use as the lamp produces UV light. A cavity filter could be avoided for this (Hg/Ar+Thallium Iodide) configuration, since the lamp has an output of 71% at mostly 535 nm. This is a band which is almost at the peak of the Ti: Al₂O₃ absorption band.

While this configuration would probably not support being used as an oscillator, this configuration would lend itself to being used as a practical amplifier. It would still be less efficient than the Alexandrite amplifier as the fluorescent decay time is twenty five times longer (75 microseconds vs. 3 microseconds) in Alexandrite at a temperature of 180 degrees Celsius compared to the Titanium Sapphire gain material. However if the designer needed to operate at longer frequencies than the Alexandrite, the Ti:Al₂O₃ system would be able to do so.

Applications

One of the several important uses of high power lasers is in Pulsed Laser Deposition (PLD). If high repetition rate Q-switched pulses (these pulses are created using one of several commercially available external switching devices applied to the example lasers discussed in this disclosure) are directed at sputter targets, then discrete layers of any atomic species or compound can be transferred to a substrate making a structured micro layered device. An improvement over even High power PLD would be the use of both versions of this laser in the target vaporization use for PLD. In this example the highest average power laser (Alexandrite producing high radiance Q switched pulses at approximately 13,333 Hz) would be used to remove target material at a high rate. A second beam at a higher repetition rate (166 kHz) from a Titanium laser operated as an ultra-fast laser is directed at the in-transit plume of ionic atomic deposition material. This double laser use would greatly improve the quality of the produced films as any ejected particulate matter would be completely converted to atomic ionized matter by the second laser.

One important example would be to deposit a Diamond Like Carbon (DLC) coating (or to deposit actual diamond coatings) on any metal mechanical substrate using the laser or a dual laser. DLC layers have at least four features that make them important for commercial applications. First, DLC has the desirable feature of being extremely hard, and a surface that is coated with DLC will virtually never show any wear. Second, DLC layers have very high thermal conductivity (several times higher than copper) which make them ideal for use as thermal spreaders to remove heat from any surface to which it is attached. Third, DLC layers are electrically insulating and have very high breakdown voltage (~10,000 volts per micron thickness). Fourth DLC has a very low coefficient of thermal expansion, permitting its use as a substrate for

fabricating integrated circuits and microelectronic devices with extremely high operating power as the DLC would conduct the heat of operation away from compact monolithic stacked circuit structures. Thus, they can be used to provide effective electrical insulation with relatively thin layers or thick wafers/slabs and stacked monolithic architected blocks for use in many high voltage or otherwise high electric field density applications.

DLC insulation applied to copper or aluminum wire used in manufacture of various products would permit a DLC insulated device to operate at higher temperatures than are possible with polymer insulation materials. The operating temperature limit for conventional polymer-insulated wire devices is 200 degrees C. By comparison, the DLC coating would function up to its graphitization temperature which begins near 400 degrees C. The combination of DLC's thermal conductivity, very low coefficient of thermal expansion, and voltage insulation permits devices to be built that are several times smaller in physical size than their polymer insulated counterparts and yet would still operate at the same power levels.

DLC coatings created by Pulsed Laser Deposition (PLD) (where the sputter target is graphite or pure carbon), have been demonstrated on small samples, but the barrier to larger scale commercial applications has been the lack of availability of low cost, higher power lasers like the slab laser disclosed herein. One implementation is to use the Alexandrite laser, such as of a design disclosed herein, to produce high average power Q switch pulses being directed at the donor sputter target, with a Titanium Sapphire version producing 166 KHz or greater pulse speeds being used at the same time and being directed at the plume (thus super pulverizing, atomizing and ionizing it) while it is in flight to the substrate. This method can be used for any sputter material, and is not limited to graphite.

Another useful commercial application is in the production of low cost solar cells or integrated circuits by PLD. Virtually any material can be deposited on any substrate in any order and thickness. The barrier to commercial applications has been the availability of a low cost high power laser source. Any of the lasers disclosed herein can be used to enable the economical high speed generation of high efficiency multi-layer PV (photo-voltaic) films such as Silicon, Germanium, Gallium Arsenide on Germanium, Gallium Nitride, Gallium Indium Nitride, Gallium Phosphide or any other Gallium Alloy, Included is the claim that any existing semiconductor ally currently in existence that has been produced by sputtering, Chemical Vapor or ion deposition on any substrate material can be produced with the described laser system or dual laser systems.

Since PLD has the lowest deposition temperature, it is now possible that PV films can be grown on suitable thermoplastic surfaces. This would provide a path for flexible PV arrays at low manufacturing cost compared to conventional MOCVD (metal organic chemical vapor deposition) methods.

High power lasers have a number of applications in the areas of welding and/or cutting. The Q switched version of the slab laser would permit steel plates to be cut that are several to tens of inches thick. 20 KW CO₂ lasers are currently being used in shipyards, but 100 kW lasers are rare and very expensive. This would not likely be the case for slab laser systems as disclosed herein, which can be made more economically. A system made up of a series of laser amplifiers, such as the examples provided in this disclosure, could deliver several times this power at much reduced operating costs, compared to other megawatt class laser systems.

A high powered laser system can also be used for tunneling and/or underground excavation. The use of a Q switched pulse train beam would permit slicing the rock face of a target excavation into thick vertical slabs. If a rectangular section under the slices were to be excavated for the use of an articulated conveyor belt material removal system, and then the cutting beam were to then be directed horizontally several feet above this space on each vertical slice then after the horizontal slices were made then the weight of the slabs of rock, would at some point break the rock free to fall onto an articulated conveyor belt system. It is possible for a 1 megawatt beam by virtue of vaporizing a 1 inch diameter hole into 22 feet of rock in about one second, to remove a 5 meter by 5 meter by one meter "panel" of rock in an hour or so, with conveyor belt mucking systems. Compact 5 megawatt systems are feasible in heavy truck mounted architectures. This would represent a 25-50 time improvement in tunneling speed.

Many other example embodiments can be provided through various combinations of the above described features. Although the embodiments described hereinabove use specific examples and alternatives, it will be understood by those skilled in the art that various additional alternatives may be used and equivalents may be substituted for elements and/or steps described herein, without necessarily deviating from the intended scope of the application. Modifications may be necessary to adapt the embodiments to a particular situation or to particular needs without departing from the intended scope of the application. It is intended that the application not be limited to the particular example implementations and example embodiments described herein, but that the claims be given their broadest reasonable interpretation to cover all novel and non-obvious embodiments, literal or equivalent, disclosed or not, covered thereby.

What is claimed is:

1. A laser amplifier device comprising:

a slab crystal configured to receive an input laser beam, said slab crystal arranged as a having a plurality of planar sides and two planar ends wherein the planar ends are not parallel to each other;

a pump light source providing light energy including a portion in an ultraviolet frequency band and a portion in a visible light frequency band; and

a cavity filter material substantially transparent to the visible light frequency band, said cavity filter material having a planar emitting surface provided adjacent to one of the sides of the slab crystal, the planar emitting surface being provided between said one of the sides of the slab crystal and the pump light source, said cavity filter material for receiving at least a portion of the light energy from the pump light source, and for converting a part of the received light energy that is at the first ultraviolet frequency band into light energy at a converted frequency band less than the ultraviolet frequency band to emit from the planar emitting surface for illuminating said one of the sides of the slab crystal, said cavity filler material being configured to be transparent to at least a part of the received light energy that is in the visible frequency band permitting the part of the light energy in the visible frequency band to illuminate said one of the sides of the slab crystal with the part of the light energy in the visible frequency band, wherein

the slab crystal is adapted to both absorb a portion of the part of the light energy in the visible frequency band transmitted through the cavity filter illuminating said one of said sides, and also to absorb a portion of the part of the light energy at the converted frequency band illu-

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minating said one of said sides, for amplifying the input laser beam for emitting an amplified laser beam from the slab laser.

2. The device of claim 1, wherein the slab crystal includes chromium doped alexandrite.

3. The device of claim 1, wherein the cavity filter material includes terbium fluoride doped with samarium.

4. The device of claim 1, wherein the amplified laser beam is emitted from the same end of the slab crystal as the input laser beam enters the slab crystal for amplification, such that the emitted laser beam is emitted from the slab crystal at a different angle than the angle in which the input laser beam enters the slab crystal.

5. The laser device of claim 1, wherein said slab crystal comprises a back reflecting surface and an end not including the back reflecting surface that is provided at an acute angle with respect to one adjoining side of the slab crystal and is provided at an oblique angle with respect to an opposite adjoining side of the slab crystal such that the emitted laser beam is emitted from the slab crystal at a different angle than the angle in which the input laser beam enters the slab crystal.

6. The laser device of claim 1, wherein the end not including the back reflecting surface is provided at an acute angle with respect to one adjoining side of the slab crystal and is provided at an oblique angle with respect to an opposite adjoining side of the slab crystal.

7. An amplifier system comprising a plurality of the laser devices of claim 1 configured in series such that an output beam from a prior one of the laser devices is used as an input beam of a subsequent one of the laser devices.

8. The laser device of claim 1, wherein the slab crystal is provided with a back reflecting surface that is not at 90 degrees with respect to the horizontal axis of the slab crystal.

9. A laser amplifier device comprising:

a slab crystal having a plurality of planar sides and including chromium doped alexandrite, said slab crystal being configured to receive an input laser beam;

a pump light source providing light energy including an ultraviolet frequency band and a visible frequency band; and

a cavity filter material including terbium fluoride doped with samarium, said filter material having a planar emitting surface provided adjacent to one of the sides of the slab crystal, the planar emitting surface being provided between said one of said sides of the slab crystal and the pump light source, said cavity filter material for receiving at least a portion of the light energy from the pump light source, and for converting a part of the received light energy that is at the ultraviolet frequency band into light energy at a converted frequency band less than the ultraviolet frequency band to emit from the planar emitting surface for illuminating said one of the sides of the slab crystal for at least partial absorption by the slab crystal, and said cavity filter material being configured to be transparent to at least a part of the received light energy that is at the visible frequency band permitting the part of the light energy in the visible frequency band to illuminate said one of the sides of the slab crystal with the part of the light energy in the visible spectrum for at least partial absorption by the slab crystal, wherein the slab crystal uses the absorbed visible frequency band and the absorbed converted frequency band to amplify the input laser beam and to emit an amplified laser beam.

10. An amplifier system comprising a plurality of the laser devices of claim 9 configured in series such that an amplified laser beam from a prior one of the laser devices is used as an input laser beam of a subsequent one of the laser devices.

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11. The device of claim 9, further comprising a plurality of elastic holders for holding components of the device while allowing for thermal expansion of one or more the components of the device.

12. The device of claim 9, further comprising a coolant circulation system for circulating a coolant in the device for cooling the slab crystal and/or the cavity filter material.

13. The device of claim 9, wherein the amplified laser beam is emitted from the same end of the slab crystal as the input laser beam enters the slab crystal for amplification, such that the emitted laser beam is emitted from the slab crystal at a different angle than the angle in which the input laser beam enters the slab crystal.

14. The laser device of claim 13, wherein the same end is provided at an acute angle with respect to one adjoining side of the slab crystal and is provided at an oblique angle with respect to an opposite adjoining side of the slab crystal.

15. The laser device of claim 9, wherein the slab crystal is provided with a back reflecting surface that is not at 90 degrees with respect to the horizontal axis of the slab crystal.

16. A laser amplifier device comprising:

a slab crystal configured to receive an input laser beam, wherein said slab crystal has at least two planar sides and has one end connecting the two planar sides that is treated with a reflective coating and an opposite end connecting the two sides that is not parallel to the one end;

a pump light source providing light energy including a portion in an ultraviolet frequency band and a portion in a visible light frequency band;

a coolant circulation system for circulating a coolant in the device for cooling the device; and

a cavity filter material substantially transparent to the visible light frequency band, said cavity filter material having a planar emitting side being provided adjacent to one of the two sides of the slab crystal, the emitting surface being provided between said one of the sides of the slab crystal and the pump light source, said cavity filter material configured to receive at least a portion of the light energy from the pump light source, said cavity filter material configured to convert at least a part of the received light energy that is at the first ultraviolet frequency band into light energy at a converted frequency band less than the ultraviolet frequency band to illuminate said one of the sides of the slab crystal, wherein the pump light source and the cavity filter material are arranged such that at least part of the received light energy in the visible light frequency band is transmitted through the cavity filter to the slab crystal for illuminating said one of the sides of the slab crystal, and wherein the slab crystal is adapted to both absorb at least a portion of the part of the light energy in the visible frequency band transmitted through the cavity filter and also to absorb at least a portion of the light energy at the converted frequency band, said absorption providing energy for amplifying the input laser beam for emitting an amplified laser beam from the slab laser.

17. An amplifier system comprising a plurality of the laser devices of claim 16 configured in series such that an emitted laser beam from a prior one of the laser devices is used as the input laser beam of a subsequent one of the laser devices.

18. The device of claim 16, further comprising a plurality of elastic holders for holding components of the device while allowing for thermal expansion of one or more the components of the device.

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19. The device of claim 16, wherein the coolant circulation system is configured for cooling the slab crystal and the cavity filter material.

20. The device of claim 16, wherein the amplified laser beam is emitted from the opposite end of the slab crystal and the input laser beam enters the opposite end of the slab crystal for amplification, such that the emitted laser beam is emitted from the slab crystal at a different angle than the angle in which the input laser beam enters the slab crystal.

21. The laser device of claim 16, wherein the opposite end is provided at an acute angle with respect to one adjoining side of the slab crystal and also is provided at an oblique angle with respect to an opposite adjoining side of the slab crystal.

22. The laser device of claim 16, wherein the end with the reflective coating is provided at an angle other than 90 degrees with respect to the horizontal axis of the slab crystal.

23. The slab laser device of claim 1, wherein said cavity filter material is configured in a slab of a size substantially corresponding to the size of the slab crystal such that said cavity filter material radiates light in the converted frequency band in a manner to illuminate substantially all of said side of the slab crystal.

24. The slab laser device of claim 1, further comprising:
a second pump light source; and
a second cavity filter material adapted to be substantially transparent to the visible light frequency band, said second cavity filter material having an emitting side pro-

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vided adjacent to different side of the slab crystal for receiving the light energy from the second pump light source, said cavity filter material configured to convert at least a part of the light energy at the first ultraviolet frequency band into light energy at a converted frequency band less than the ultraviolet frequency band to illuminate said one of the sides of the slab crystal.

25. The slab laser device of claim 24, wherein said second cavity filter material is placed between said slab crystal and said second pump light source.

26. The device of claim 1, wherein the slab crystal is provided with a reflecting surface which includes a silicon dioxide coating or dielectric multi-layer $\frac{1}{4}$ wavelength stack comprising a tuned or frequency selective behavior for the input laser beam but transparent to the pump light.

27. The device of claim 1, further comprising a plurality of elastic holders for holding components of the device while allowing for thermal expansion of one or more the components of the device.

28. The device of claim 1, further comprising a coolant circulation system for circulating a coolant in the device for cooling the slab crystal and/or the cavity filter material.

29. The device of claim 24, wherein the slab crystal includes chromium doped alexandrite.

30. The device of claim 24, wherein the cavity filter material includes terbium fluoride doped with samarium.

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